

Combined Heat and Power for Saving Energy and Carbon in Residential Buildings

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ABSTRACT

Combined Heat and Power (CHP) systems can simultaneously deliver thermal and electric (or mechanical) energy services and thus use fuel very efficiently. Today's small-scale CHP systems already provide heat, cooling and electricity at nearly twice the fuel efficiency of separate heat and power based on power remote plants, electric chilling, and onsite hot water and space heating. In this paper, we have refined and extended our earlier methodology used in assessments of small-scale CHP for commercial buildings, to homes. Recent U.S. and European technology, policy and market developments make the adoption of such "microCHP" technologies by 2010 more likely. Solid oxide and proton exchange membrane fuel cells, reciprocating gas engines and stirling engines are currently being tested for residential applications. The second part of the paper compares gas fired microCHP systems with traditional gas fired furnaces and water heaters for typical single family homes in New England where high electricity costs, net metering and high thermal-to-electric ratios make microCHP more attractive. Our model provides 1) the allowable turn key cost premium, \$1,444 for a 4-year payback and an assumed \$100 additional annual maintained cost, and the 2) carbon reductions, 29% or 0.8 Mt_c (metric tons of carbon equivalent).¹ The complete study with additional market segments, scenarios and uncertainty analysis will be available at <http://gwu.edu/~deppe/chp.htm> or can be requested at a.deppe@gmx.net.

Background/Motivation

Buildings account for 12% of the direct fossil fuel consumption and 36% of the electricity generated and 25 % of the nation's fuel bill. By consuming this amount of energy, the building sector is also responsible for 30-40% of all airborne pollutants and carbon generated. The building sector can be broken down further into 42% single-family residences, 14% multifamily residences and 44% commercial buildings. Our previous paper examined the potential for small-scale CHP in commercial buildings. This paper examines the potential for CHP in residential homes at the case of single-family residences in New

¹ Here and elsewhere the term "carbon" refers to carbon dioxide (CO₂), a major greenhouse gas in carbon-equivalent units = 12/44* mass of CO₂

England

In 1997 (EIA 1999) 10.7 Quads of primary energy was used to provide the 3.5 Quads of site electricity used by U.S. residences. The remaining primary energy 7.2 Quads, was dissipated as waste heat. This waste heat corresponds almost exactly to the residences' heat requirements (7.1 Quads). The huge losses of the electricity system (relative to the losses from space and water heating) means that while electricity accounts for only 35% of "site" energy, it accounts for 61 percent of the primary energy use and the same or more pollution. If the electricity used in residences buildings were generated by microCHPs and all the waste heat could be used, residential energy use could be reduced significantly. Because residential loads are quite uneven, and because we already have a grid this is not feasible. But our model shows that a fuel cell CHP system that has an electric efficiency similar or better than the grid can supply 40% of a typical residence's thermal demand by using its waste heat. These CHP systems already exist, although they are not yet economical.

None of the other recent studies that examine the potential of CHP to save energy and reduce carbon comprehensively examines available and soon-to-be-available residential or micro-scale (less than 10 kW) CHP for residential buildings. This is understandable since there is currently no U.S. capacity in this size range. But as we shall describe, we believe significant growth in this area is possible—though no significant U.S. market will develop before 2010. Over the next decade more efficient, and lower-cost microCHP systems will become available. Other technical factors that favor residential microCHP are the excellent part-load characteristics of new microCHP technologies. Market factors that favor microCHP include net metering policies that allow home owners can use the grid as "virtual power storage" and utilities need for additional distributed capacity to increase reliability and meet mid-day peaks without construction of more transmission and distribution.

Characteristics of MicroCHP Technologies

This section describes four micro CHP prime movers. Each technology faces numerous challenges detailed in the following.

A) Fuel Cells

Fuel cells have a much higher electric efficiency than combustion-based generators that rely on a 3-step heat-mechanical-electromagnetic process that is constrained by the thermodynamics of heat engines. Heat engines' maximum theoretical efficiency cannot exceed the Carnot limit, which in practice limits engines to far less than 60 percent efficiency. A fuel cell comprises two electrodes that sandwich an electrolyte (a material that allows ions but not electrons to diffuse through it). The electrode pulls off the electrons, which exit through an external circuit while the ions diffuse through the electrolyte. At the other electrode, the electrons recombine with the ions.

Of the five different fuel cell technologies under development (Kaarsberg et al 1999b) only two, the low temperature proton exchange membrane fuel cell (PEMFC) and the high temperature Solid Oxide Fuel Cell (SOFC) are being engineered for residential applications. They are currently not yet commercially available. A major barrier to fuel cells is their first

cost. But residential FC developers hope to reduce MicroCHP package costs to less than \$1000/kw by 2010. There is reason to believe they will succeed, since 1997, several demonstration units have been installed and corporations are investing millions of dollars. Fuel cells produce negligible amounts of pollution (e.g. NOX at 0.005 lb/MWh_(t+e)), operate at very high electric efficiency (up to 45% electric) and because they have no moving parts, are very quiet.

1) Solid Oxide Fuel Cells. SOFCs use an advanced ceramic, solid zirconium dioxide, operated at nearly 1000 °C as an electrolyte. The SOFC is the newest of the five fuel cells designs. A key advantage of the SOFC is that fuels other than pure hydrogen can be used. The O²⁻ oxygen ion, the oxidant, not a proton migrates through the zirconium ceramic electrolyte. The system efficiency also does not degrade with small amounts of carbon monoxide (CO). Thus, SOFC is fuel-flexible and requires little fuel pretreatment. SOFCs also do not require compressor and heat recovery is simple. The high temperature heat generated can be used directly in the reformer for fuel pretreatment and/or for heating or even to drive an absorption air conditioner. The temperatures are still low enough to avoid the formation of NO_x.

Disadvantages of the system include relatively long start up times. The prototypes now require several hours to begin operating from a cold start. Another disadvantage is the high materials cost and potential high wear due to the high operating temperature. However, because of the avoidance of the fuel processing, the SOFC stack can be nearly twice as expensive as the PEMFC stack and still be competitive. One manufacturer to be available predicts a 1 kW SOFC designed for operation on natural gas, by 2001. The electrical power will amount to about 1 kW with an electrical efficiency of about 30% at full load and 40% at partial load. The overall efficiency is targeted to be around 90%. There are no cost estimates published yet. (Schmidt 1999)

2) Proton Exchange Membrane Fuel Cells. PEMFCs are a type of polymer electrolyte membrane fuel cell that use a membrane (Nafion) as an electrolyte. Because of the membrane's thermal properties PEMFCs operate at a relatively low (80°C) temperature. But this is more than sufficient for hot water and space heating applications. The low temperature means the startup time is fast and the materials wear is low. Because of its low temperature and fast start, the PEM is the favorite fuel cell for transportation applications. Fuel cell technology was chosen by the major American carmakers as a finalist for the 3X efficiency (50-100kW) car being developed as part of the Partnership for a New Generation of Vehicles. Transportation R&D and large-scale manufacturing could reduce costs to less than \$600/kW by 2010.

Because it is the H⁺ hydrogen ion (or proton) that crosses the electrolyte, the fuel must be hydrogen. In addition, the hydrogen must be very pure since CO binds permanently to the platinum in the catalyst. More than 20 ppm CO degrades PEMFC efficiency significantly. In the absence of hydrogen infrastructure, hydrogen must be extracted from natural gas. Even after the reformers strip off the hydrogen molecules they will leave both carbon dioxide and carbon monoxide as byproducts. Typically 2000 ppm of CO remains in the reformat. The only available CO cleanup technology also consumes hydrogen, further lowering the efficiency and adding to the cost. The stack is roughly 1/3 of the total PEM fuel cell cost with fuel processing taking up another 1/3 and power inversion and conditioning the

other 1/3. Another disadvantage is that the platinum catalyst is expensive (the single largest cost for the fuel cell stack) and likely to become more so if PEMFC makers hit their manufacturing targets. Still, several manufacturers are planning to offer a commercial PEMFC in the 2001-2002 time frame. The fierce worldwide competition for low emissions automobile engines is expected to speed cost reductions in PEM fuel cells.

B) Engines

3) Reciprocating Natural Gas Engines. In such systems, the engine drives an electric generator while the heat from the engine exhaust, cooling water and oil generates steam in a boiler. No U.S. manufacturer makes package CHP systems of less than 25 kW. In the newly deregulated German electricity market, however, more than 3,000 residential sized gas engine microCHP packages have been sold to date. The most popular model is the 5-kWe model made by Senertec.² At \$15,000/kW turn key costs and with an additional maintenance cost of 2.5 cents/kWh, however, these units are not viable for the U.S. market. In Germany, they are attractive for a number of reasons. In addition to much higher base fuel costs, German residential customers must pay 0.3-cents/kWh eco taxes on natural gas and a 2.5 cents/kWh eco tax on electricity that will increase to 4 cents. CHP systems smaller than 2 MW with system efficiency of more than 70% (LHV) are exempt from these taxes. In addition, Germany requires all electric generating companies to have a certain percentage of CHP. Those that do not have enough can buy CHP credits from homeowners and others with CHP systems. The required CHP credits are targeted to double CHP from 5% of power generation to 10% by 2010.

Though it is already taking off in Europe, we estimate there will be very little U.S. market for residential engine based CHP. When measured on a performance basis (i.e., including thermal energy in the denominator), the NO_x emissions of small engines are fairly low, but still higher than the other technologies'. But US regulators do not give credit for high efficiency or electricity displacement so they are likely to require expensive end-of-pipe controls that reduce the efficiency (Kaarsberg et al Bluestein 1998). In addition to the emissions problem, their high maintenance cost and high noise levels make them a poor fit for the U.S. residential market. Engines also have relatively poor part load efficiencies and are thus not as well suited to residential applications as the other technologies.

4) Stirling Engines. The Stirling Engine—so named because it is based on the Stirling thermodynamic cycle-- was conceived more than a century ago. The Stirling engine itself is a heat recovery device, like the steam turbine. Stirling engines produce power not by explosive internal combustion, but by an external heat source. Until recently, however, reliability problems have limited their use to hobbyists. Recent test results of “free-piston” Stirling have increased confidence in them. For example, one companies free-piston Stirling engines has demonstrated more than 50,000 hours of continuous operation on single engine/alternator and more than 150,000 hours on composite machines. But this high level of availability applies only for the Stirling generator and does not include the heat source. In addition, it is only in the past decade that a viable “free-piston” Stirling was developed. All Stirling engines can be operated on a wide variety of fuels, including all fossil fuels,

² For more details visit <http://www.Senertec.de>

biomass,³ solar, geothermal, and nuclear energy. When used with fossil and biomass fuel, the continuous-combustion heater head avoids temperature spikes and makes emissions very low and easy to control.

Stirling engines⁴ closely couple a burner to a heater-head heat exchanger that induces harmonic oscillations in a piston inside a hermetically sealed container (White et al 1996). The piston power is delivered directly by an integral permanent magnet linear alternator to produce alternating current power at any desired voltage. Stirling engines have been demonstrated at power levels up to 150 kW, but the new free piston flexure-bearing versions are best suited to power levels below 10 kW – well suited to residential applications. These types of Stirling engines are especially simple devices that unlike most prime movers require little additional hardware to produce 50 or 60 Hz alternating current. Their natural vibration frequency is near 60 Hz when tuned as mechanical spring-mass-damper resonators. Thus, they can be directly attached to the electric power grid without intermediaries – further reducing cost. On the other hand, the combustion system—comprising a heater head, and air preheat systems--does tend to be relatively sophisticated. Like the steam turbine, Stirling engines can be used with heat recovery as an additional cycle for one of the other prime movers. Because a continuous combustion burner powers them, their emissions are quite low. Recent data shows NOx emissions of less than 10 ppm from an uncontrolled Stirling generator.

Europeans are bullish on Stirling Engines for microCHP. Several European utilities are demonstrating this technology for residential applications. In order to keep the cost down, Europeans have developed a very simple system with minimal heat exchangers and thus low electric efficiency. In higher value applications electric efficiencies of more than 40% and system efficiencies of more than 95 have been achieved. When commercialized in the 2002-3 time frame, the Stirling micro-CHP packages are targeted to cost \$2,500/kW(thermal+electric). Theoretically, Stirling engines should have very high availability and reliability. Service intervals of between 3,500 and 5,000 hours (equivalent to over one year's economic operation) are expected with a product lifetime of more than six years continuous operation. In the newest designs, previous vibration and reliability problems have been addressed by mounting the piston that produces the power on flexure bearings that avoid rubbing, while the tight clearance seals that are self-centering have no gas bearings or other ports. New designs with moving-iron linear alternators avoid mechanical stresses associated with other alternators and are easier to thermally integrate, reducing required burner temperature—another historic drawback.. Although Stirling engines have the potential to penetrate the U.S. market, we do not include them in our model because they are currently not eligible for net metering in most New England states.

Comparison of residential micro CHP technologies to separate heat and power (SHP)

Table 1 shows by which factor microCHP efficiencies exceed those of separate heat and power. Using the methodology described in our earlier paper (Kaarsberg et al 1998) we calculate the SHP needed to match 1 unit of fuel into each of the four microCHP technologies. Thus the seventh column of Table 1 is the SHP fuel needed to produce the

³ Biomass can be used many ways, including direct combustion, two-stage combustion, and (the cleanest) with a gasifier.

⁴ The Stirling engine operates on the thermodynamic cycle named after Scottish minister who invented it.

same amount of electricity and thermal energy as the CHP unit.

Table 1. Comparison of the main residential micro CHP technologies to SHP

1 kW unit	Electric η^5 %	Thermal η %	Temperature Range	System η %	T/E	SHP/CHP fuel
PEM Fuel Cell	29	46	80—100 °C hot water	76	1.59	1.59
SOFC Fuel Cell	27	45	80—1000*°C hot water- high quality steam	82	1.67	1.51
Engine	25	56	90—120 °C hot water, low-grade steam	81	2.24	1.59
Stirling	14	75	80—700* °C hot water- med. quality steam	89	5.36	1.48

*Depending on recuperation

Analysis of a Residential Fuel Cell MicroCHP Market in New England

Next we describe our analysis of the residential fuel cell micro CHP market for single-family homes in New England in 2010. We compare the traditional separate heat and power system of a gas furnace and gas hot water system with a gas fuel cell microCHP system to answers the following questions:

- At what additional initial investment and maintenance cost and can fuel cell microCHP systems compete with a traditional gas fired systems?
- What are the energy savings and CO₂ reductions for a typical house?

Fuel Cell and Residential Building Model

At first glance, residential applications may seem poor candidates for microCHP. Conventional wisdom is that for microCHP to make sense, there must be long and constant heat and power demand. The average home, by contrast has morning and evening peaks with low demand throughout the rest of the day. But the conventional wisdom stems from the limitations of traditional technologies and markets. Traditional CHP systems were too big and had poor part load efficiency. New one kW electric fuel cell micro CHP systems with 40% electric part load efficiency are under development.⁶

The first U.S. residences that are likely to install or retrofitted with to use fuel cell

⁵ η is the symbol we use for thermodynamic efficiency calculated at Higher Heating Value. To convert to lower heating value, multiply by 1.1.

⁶ For more details visit www.hexis.com

microCHP are most likely be in the New England. The market is favorable as it has high residential power prices, a cold climate leading to high thermal demand and an advanced deregulation of the power market. Another difference is that, as shown in Table 2, fuel cells are now eligible for “net metering” in all the New England states, except New Hampshire. With net metering homeowners can set microCHP units to operate when there is thermal demand and use the grid as “virtual power storage” at little or no extra cost.

Table 2. Net Metering Policies in New England States

	Connecticut	Maine	Massachusetts	New Hampshire	Rhode Island	Vermont
Who is eligible	All CHP	Fuel cells	Fuel cells	Not available	Fuel cells	Fuel cells
Upper Limit (kW)	50	100	60	-	25	15
Net Metering cycle/ Net energy generated (NEG)	Monthly/ NEG. purchased at avoided cost	Annual/ NEG. granted to utilities	Monthly/NEG. purchased at avoided cost	-	Annual/ NEG. granted to utilities	

Model Description

We assume microCHP units will replace gas heat and hot water systems when it makes economic sense. The residential fuel cell system market demand is determined by gas heating system replacements or new installations. Replacement of existing system heating systems that have not reached their useful lifetime is not economical.

This initial model does not take into account other market drivers, utilities that use residential microCHP to reduce peak demands for the grid, or residential homeowners that are willing to pay premiums for backup power, nor does it account for market barriers as fire codes, interconnection requirements.

In the first step a representative typical single family home was simulated in DOE2. In a second step the shape of a thermal demand curve with an hourly resolution, and the monthly energy demand is generated with DOE-II while using on Boston climate data and a typical user behavior.⁷

The data was then normalized to the average heating and power demand for single family homes in New England. In a third step a cost model determines the optimal fuel cell microCHP system size and configuration for our reference building. After that the operation of the traditional SHP and the microCHP system are simulated for each hour of the year based on the previous generated thermal and power load curves. Then gas and power costs are calculated. Another sub model determines the optimal gas furnace and its annual gas cost. This determines the average annual fuel cost savings of the CHP system. The allowable additional turnkey cost premium is then calculated based on a 4 year target payback time and the determined additional maintenance costs of the CHP system. In a last step a sub model calculates the energy savings and CO2 reductions.

⁷ Source: (<ftp://DOE2.com/Weather/TMY2>)

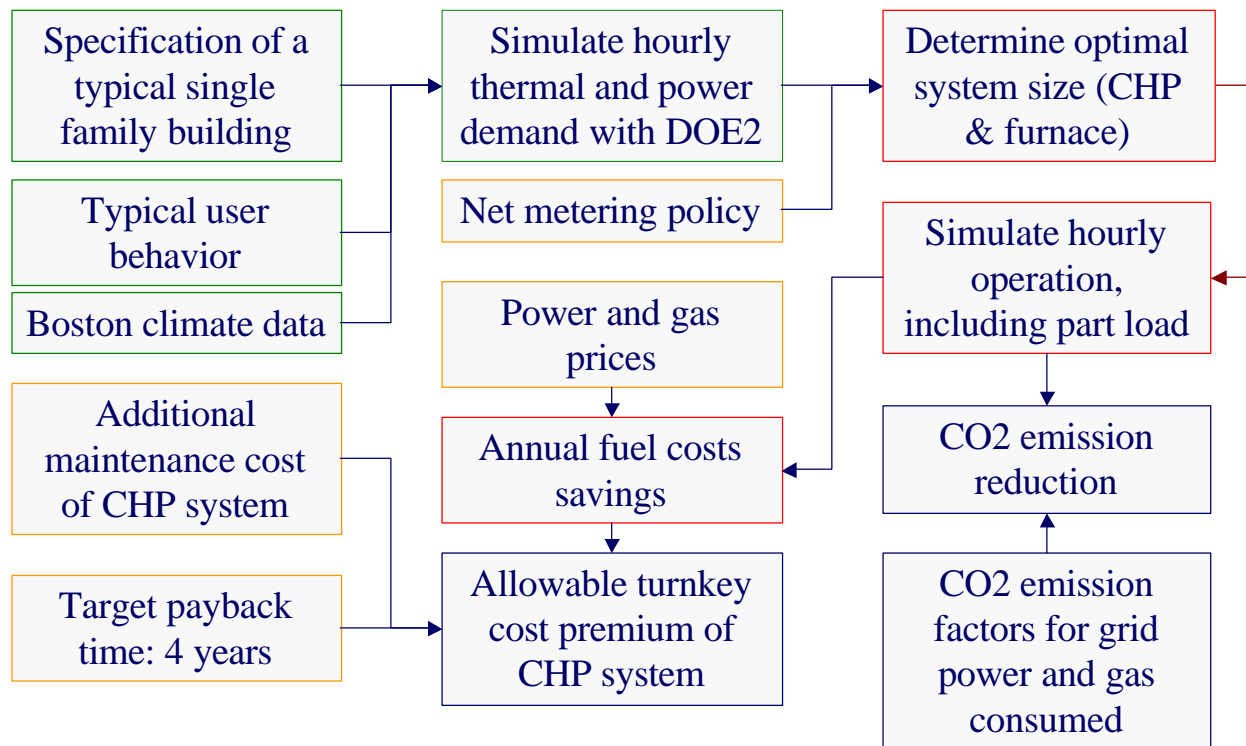


Figure 1. Comparison Model: Fuel Cell MicroCHP versus Separate Heat and Power .

Model Input and Assumptions

The average single-family home in New England has an annual power consumption of 7,062 kWh and its gas consumption for heat and hot water is 103 MBTU per year. We assume the microCHP heat displaces a natural gas burned furnace with 78 percent efficiency for space heat and grid power with 30% system efficiency. This would be the case for a new building or most retrofits. The assumed system efficiencies are shown below.

The model determines the smallest system necessary to provide all the power needs of the system while using all of the waste heat. We use this criterion because systems that provide less than the full power requirement cost more because the system cost savings are less than the avoided power costs. This kind of system and operation optimization is made possible by net metering that allows the homeowner to use the grid as virtual power storage. We also assume that the switchgear needed to permit back feeding to the grid will be economical by that time. This leads to the case where the system should generate all power while using the net as virtual power storage.

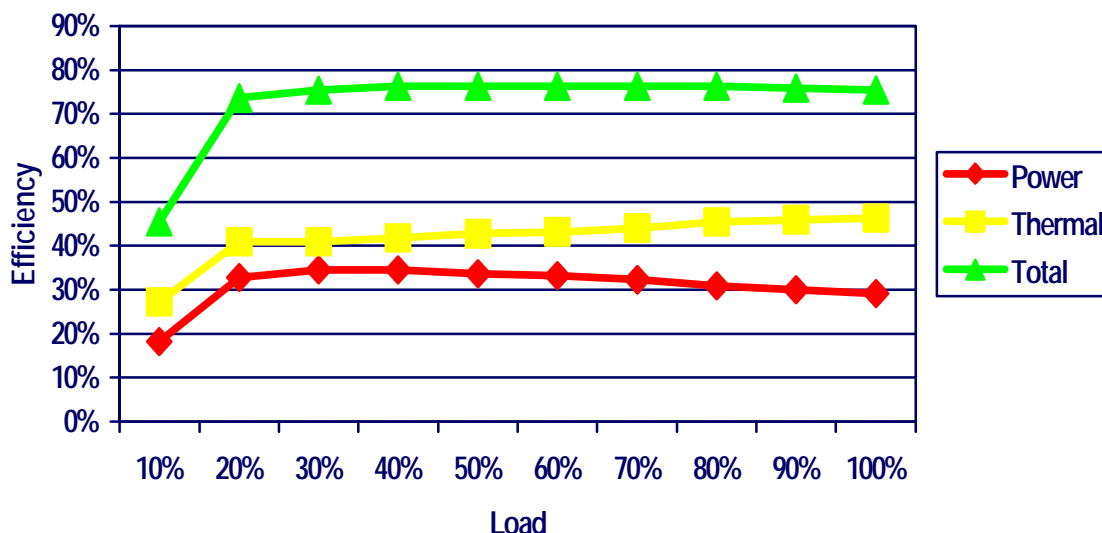


Figure 2. Fuel Cell CHP System Efficiency as a Function of Load.

Because the thermal to electric ratio of the demand is far higher than provided by the microCHP, additional heat must be supplied. Average power prices in New England are predicted to be 10 cents/kWh by 2010, gas prices 2.5 cents/kWh.

The CO₂ emissions are 50 g CO₂/kWh for the gas consumed and 181.6 g CO₂/kWh for power received from the grid. (Kaarsberg et al 1998). The other options are listed in table 3 below to show that the assumptions used are in the middle of the range of reasonable possibilities.

Table 3: Different SHP Displacement Options

Displaced SHP Site Power	Displaced SHP Heat
marginal coal (289g/kWh)	Electric space & water heating (321g/kWh)
U.S. Grid (182g/kWh)	Average Gas space and water heating (68 g/kWh)
CCGT (97g/kWh)	High efficiency Gas space and water heating (58 g/kWh)

Results

The annual power cost of a traditional system for a typical single family home in New England are \$706, the gas cost are \$737 for heating and domestic hot water. The CO₂ emissions are 2.8 tons/year. The optimal system size of the fuel cell microCHP system is 1kW_{el}. The resulting thermal power of the fuel cell is 1.6 kW. The small size allows the system operate virtually all year around while still using all the waste heat, mainly for domestic water heating. The waste heat from the fuel cell would cover 41% of the thermal

load. The system would reduce total fuel costs by 464\$ and CO₂ emissions by 0.8 tons or 29%. In other words, to achieve payback times of 4 years or less, a microCHP system would be allowed to have additional turnkey costs of \$1,442 compared to the traditional system, if we assume additional maintenance costs of 100\$ per year.

Conclusion

We now have shown that by 2010, microCHP could be an important technology for saving energy and carbon in residences. In 2010 we estimate that microCHP fuel cell systems in single family homes in New England will emit on average 29% less carbon than separate heat and power (SHP) and avoid the emission of 0.8 tons of carbon. To put this in perspective, the average car emits 1 ton of carbon per year, so installing fuel cell microCHP is equivalent to not driving a car for more than 10 months.

Because of a nexus of several factors, 1) current and impending improvements in microCHP, 2) electricity deregulation, 3) climate change concerns and 4) electric reliability concerns, residential microCHP is an important opportunity. To capture this opportunity, homebuilders, energy experts and policymakers must work together. In addition to improving technologies and developing incentives, for any significant deployment of microCHP, environmental and utility related barriers must be overcome (Munson & Kaarsberg, 1998). A recent study (Alderfer, Eldridge & Starrs, 2000) documents utility related barriers faced by small-scale generators seeking to connect to the electricity system. The market barriers are real, and that they are, in part, an artifact of the present electricity industry institutional and regulatory structure designed for a vertically integrated utility industry relying on large central station generation. An integrated approach to saving energy on both sides of the electricity meter will enable the most productive, and lowest carbon use of electrical, mechanical and thermal energy in buildings.

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